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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

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VALIDATION OF THE STANDARD SHIP MOTION PROGRAM, SMP: IMPROVED ROLL DAMPING PREDICTION

by

A. E. Baitis

W. G. Meyers

and

T. R. Applebee

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SHIP PERFORMANCE DEPARTMENT

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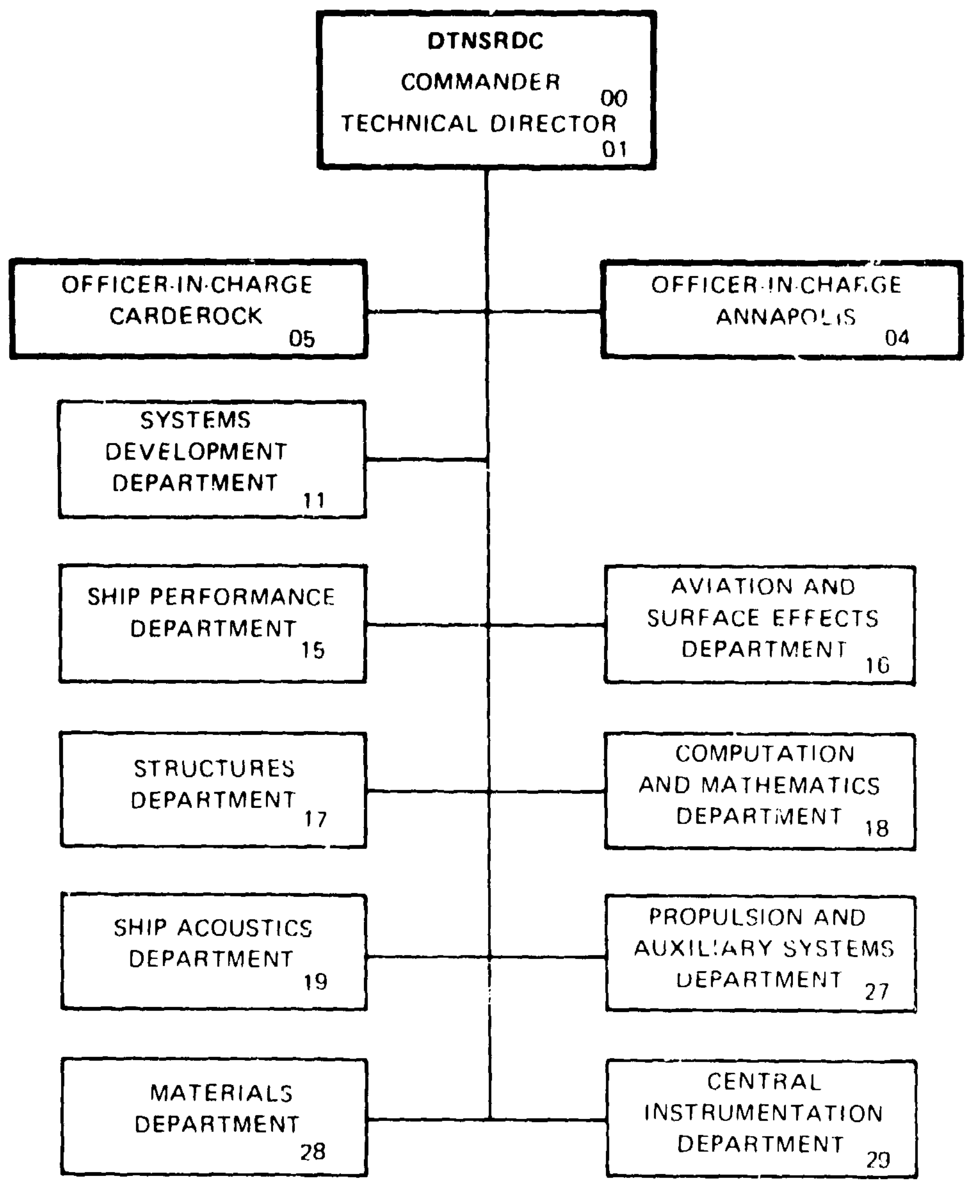

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Refinement in calculating the roll damping characteristics of surface ships, particularly in the speed-dependent lift damping terms, has significantly improved the prediction of lateral ship motions. Incorporation of these refinements into the new revised ship motion computer program has greatly enhanced the accuracy and usefulness of the program. Validation of the roll damping computations is presented in this document through the

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ABSTRACT

Refinement in calculating the roll damping characteristics of surface ships, particularly in the speed-dependent lift damping terms, has significantly improved the prediction of lateral ship motions. Incorporation of these refinements into the new revised ship motion computer program has greatly enhanced the accuracy and usefulness of the program. Validation of the roll damping computations is presented in this document through the comparison of computer-predicted damping with model test data for a number of ships. Relatively good agreement is found between the analytical and experimental results.

ADMINISTRATIVE INFORMATION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) was authorized and funded over a period of years to perform this investigation. For fiscal years 1977 and 1978, funding was provided by the Independent Exploratory Development (IED) Program under Project Number 62766N and Block Number ZF-61-412-001, identified at DTNSRDC as Work Unit 1568-124. For fiscal 1978, funding was also provided by the Naval Sea Systems Command (NAVSEA) under Work Request 81650 and identified at DTNSRDC as Work Unit 1568-806. In addition, the Conventional Ship Seakeeping Research and Development Program funded this investigation under Project Number 62543N, Block Numbers SF-43-421-001 and SF-43-411-212 in 1978 and 1979, respectively. Work Unit identification at DTNSRDC for this funding was 1504-100. Funding for 1980 was provided by the Ship Performance and Hydromechanics Program under Project Number 62543N, Block Number ZF-43-421-001, identified as Work Unit 1500-104. Fiscal 1981 work is funded by the Surface Ship Hydromechanics Program under Project Number 62543N, Block Number SF-43-400-001, identified as Work Unit 1507-101.

INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center's Ship-Motion and Sea-Load (SMSL) Computer Program[1,2*] has recently been completely revised. This task was performed in order to provide a standard U.S. Navy Ship Motion Program (SMP)** to all U.S. Navy research and development and design agencies. In addition, this program was updated to improve basic computational procedures as well as to enhance its usefulness as a ship design tool. One of the major improvements in the new program is a significant increase in the accuracy of the roll motion predictions.

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*A complete listing of references is given on page 9.

**Meyers, W.G., T.R. Applebee and A.E. Baitis, "User's Manual for the Standard Ship Motion Program, SMP," Report DTNSRDC/SPD-0936-01 to be published.

In order to validate the motions predicted by the SMSL program at various headings, speeds, GM's, roll radii of gyration and bilge keel sizes, free-running model experiments with the DE-1006 model were performed at DTNSRDC in the early 1970's. These experiments[3] indicated that the roll damping calculated by the SMSL program was inadequate, particularly at low GM's and high ship speeds. The subsequent analytical work of Schmitke[4] found that the reason for this inadequacy was the neglect of the very important speed-dependent lift damping of the appendages, particularly for the rudders which had not been previously included in the calculations.

As a result, the newly revised SMP calculates the roll damping by a procedure which also includes lift damping terms due to the hull and its appendages. Since SMP can output all the component parts of the roll damping coefficients plus their totals for any candidate ship, direct comparisons between the SMP-predicted roll damping and the results from model test data are made herein.

Thirteen ships at various speeds, configurations and loading conditions are compared.

SHIP PARTICULARS

The ships used in this investigation are divided into four classes:

1. Aviation ship hulls - the CVV and the Sea Control Ship (SCS);
2. Cruiser-type hulls - the CSGN with large waterplane (LWP) and conventional waterplane area designs, and the CGN-42;
3. Destroyer/Frigate-type hulls - the DD-963, the FFG-7, the DE-1006, and the USCG 270-ft Medium Endurance Cutter (WMEC);
4. Auxiliary hulls - the AOE, the AO-177, the T-ARC, and the MCM.

A listing of the hydrostatic characteristics of each ship is presented in Table 1 and Figure 1 contains the computer-drawn underwater hull shapes.

ANALYTICAL APPROACH

A major improvement in SMP is the inclusion of previously neglected but very important, speed-dependent dynamic lift damping due to the hull and appendages. The SMSL program's computational procedure for the roll damping coefficient, designated as B_{44}^{T}, is defined as

$$B_{44}^{T} = B_E + B_W \qquad (1)$$

Here roll damping is treated as the sum of two terms, B_E being roll angle dependent (viscous) and B_W being roll angle independent (potential). SMP calculates the roll damping as the sum of three terms, where the third term, B_L, represents the dynamic lift damping of the hull and appendages. The roll damping coefficient is now defined as

$$B_{44}^T = B_E + B_W + B_L \tag{2}$$

B_L is dependent on speed, the geometry and center of pressure of the lifting surface, and the location of the roll center. B_W is calculated using potential theory in essentially the same fashion as was done in the older program.[1,2] B_W is speed independent though it is dependent upon the frequency of wave encounter. B_E is similarly calculated using the procedures of the old program with certain modifications due to more recent Japanese work. B_E is regarded as being dependent on speed, roll angle, frequency, and ship or appendage geometry. The viscosity-related damping is composed of the following components

$$B_E = B_{BK} + B_{SF} \times F_2(V) + [B_{Hull} + B_{App}]F_1(V) \tag{3}$$

B_{BK} is the bilge keel damping calculated according to the expressions of Kato.[5] B_{SF} is the damping due to hull skin friction and calculated in accordance with the procedures of Kato;[6] the function $F_2(V)$ is the speed dependence of this skin friction damping in accordance with Tamiya and Komura.[7]

B_{Hull} is the eddymaking damping due to the hull calculated according to the procedures of Tanaka[8] with minor modifications. For the appendages, B_{App} represents the flat plate eddymaking damping calculated using the empirical data of Hoerner.[9] The speed dependence of these two eddymaking damping components is introduced by using the function $F_1(V)$ in accordance with the work of Ikeda, Himeno and Tanaka.[10] It is to be noted that the modular nature of SMP will simplify the anticipated future changes in the calculation procedures for several of the roll damping components as the theory becomes more refined.

In calculating B_L, the hull contribution is obtained by considering the entire hull to be a very low aspect ratio foil, and each appendage contribution is calculated separately. Here it should be mentioned that the appendages considered are bilge keels, skegs, rudders, fins and propeller shaft brackets. It should also be

noted that the skegs are treated as an integral part of the hull section for the Tanaka eddymaking damping calculations. However, they are treated as separate appendages for purposes of dynamic lift damping calculations.

Examples of predicted roll damping using this analytical procedure versus experimental roll damping results from free-running model roll decay tests are presented in Figures 2 through 5.

EXPERIMENTAL DATA

A standard experimental procedure is used at DTNSRDC to investigate the roll damping characteristics of surface ships. A free-running model experiment is performed in calm water to determine the nondimensional roll decay coefficient for various mean roll angles. The details of the experiment are given below.

The self-powered model is brought up to a predetermined speed on a straight course, restrained in sway, yaw and surge. The model is then released from all restraint, and roll motion is induced by pushing down on the side of the model. The induced roll motion occurs at the natural roll frequency of the model and decreases in magnitude in successive motion cycles. This decay of the motion is considered to be representative of the total roll damping. Thus roll decay due to coupling between roll, sway, and yaw is assumed to be negligible. A time history of the roll motion that the model experiences is measured and recorded on an analog strip chart, such as shown in Figure 6. This procedure is repeated for each speed over a range of different initial roll angles. The roll decay coefficient, n, is determined from these analog records by the formula:

$$n = \frac{1}{2\pi} \ln \frac{\phi_1}{\phi_2} \tag{4}$$

where ϕ_1 and ϕ_2 correspond to consecutive double amplitude roll angles (see Figure 6). Each value of n has a corresponding mean roll angle, $\bar{\phi}$, associated with it, where

$$\bar{\phi} = \frac{1}{2} \left[(\phi_1+\phi_2)/2\right] \tag{5}$$

Simply stated, $\bar{\phi}$ is the average single amplitude roll angle. Then pairs of values, n and $\bar{\phi}$, can be plotted for comparison with analytical results as shown in Figures 2

through 5. All of the experimental roll damping data shown represents roll damping at the natural roll frequency.

It should be noted that sizable variations in the roll decay coefficient may occur under conditions where roll angles are small or model speeds are high. Accuracy can be lost in both recording and analyzing small roll angles. At high speeds (e.g., 20 knots full scale), only several cycles in the roll decay process can be obtained. Moreover, as speeds increase, the ability to excite the model in roll alone without inducing extraneous sway and yaw motions is greatly diminished. Often only the first two cycles in the decay record can be considered reliable.

For these reasons, the roll decay coefficient corresponding to the initial two roll decay cycles is regarded as the most accurate and dependable. These points have been blackened in Figures 2 through 5.

The experiments to determine the roll damping characteristics of the ships presented in this report have been conducted over the years at DTNSRDC. The ships and corresponding references for the original data are as follows: CVV*, SCS*, CSCN[11], C[illegible]-[illegible]2*, FFG-7[12], WMEC[13], AOE[3], AO-177*, and MCM*. The roll damping experiment for the T-ARC was performed by Hydronautics, Inc.* Roll decay data for the DE-1006 and DD-963 was provided from model experiments conducted by Baitis and Rossignol, respectively, both of DTNSRDC.

COMPARISON OF RESULTS

Comparisons between the calculated and measured roll damping characteristics of the 13 ships investigated are made in Figures 2 through 5. Results are presented in terms of the nondimensional roll decay coefficient as a function of the single amplitude mean roll angle. This decay coefficient represents, in accordance with the nomenclature of Cox and Lloyd,[14] the ship damping moment per unit roll rate, nondimensionalized by the product of twice the natural roll frequency and the total mass moment of inertia of the ship about the roll axis. The experimental data, represented by circles, are either darkened to indicate the decay coefficient associated with the initial roll amplitude or open to indicate coefficient values from subsequent roll amplitudes (see EXPERIMENTAL DATA, page 4). SMP-predicted roll decay is represented by the solid line. Each plot for each ship has a speed, in

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*Documents reporting the results of roll damping experiments for these ships have limited distribution.

knots, and a Froude number, in parentheses, associated with it. In some cases, experimental data may not be available. In the case of the T-ARC at 20 knots, no data is available.

In general, good agreement is illustrated in these comparisons. The slope of the roll damping with increasing roll angle is an indication of the nonlinearity of roll damping and is quite well predicted by theory. Tendencies are for the analytical results to overpredict the damping at lower speeds and to underpredict at the higher speeds.

One outstanding exception is the case of the AO-177 in Figure 5. Predicted roll damping grossly underestimates the measured data at every speed. Because this is the only case of the 13 ships where the comparison suffers notably at all speeds, it is felt that the original experimental data may be in error. This is supported by the relatively large amount of damping measured for this ship which has no bilge keels. A similar vessel, the AOE, as presented in Figure 5, demonstrates significantly less damping (on the order of one-half or less) than the AO-177 when tested without bilge keels.

The effect of speed on the roll damping is presented for three different bilge keel sizes, in Figure 7, for the DE-1006 at its nominal base GM of 12 percent of beam. BK4 represents the hull without bilge keels, BK3 represents bilge keels with an area of 1.25 percent of the wetted area of the hull, and BK1 represents the nominal base bilge keel with a 2.54 percent of wetted area size. These results are shown for speeds of 0, 9, and 27 knots corresponding to Froude numbers of 0, 0.15, and 0.46. The agreement between the slopes of the experimental and calculated roll damping suggest that the roll angle dependent eddymaking damping, B_E, is essentially correct. Similarly, the growth of the damping with increasing speed which was not present in the earlier program, where B_L was neglected, appears to be reasonably well represented.

The bilge keel effect at zero speed is presented for the three GM's in Figure 8. The lift dependent damping B_L is therefore zero in this figure. GM1 represents the nominal base value for the ship of 12 percent of beam, GM2 represents 9 percent of beam value, and GM3 represents the smallest tested GM of 6.1 percent of beam. Again, the eddymaking damping component B_E appears to be generally correct since the measured and calculated slopes agree. GM does not significantly affect these slopes as expected, although bilge keel size does. As the bilge keels become larger, the

amount of eddymaking damping relative to the total damping increases, and thus the nonlinearity of damping with roll angle increases.

The adequacy of the roll angle independent damping term, B_W, on the other hand, is less certain since the agreement between the zero roll angle intercept value of measured and calculated damping with GM is much poorer. Note for example these discrepancies for BK1.

Figures 9 and 10 were prepared to illustrate the values of various damping components predicted by SMP as well as their sum. Both figures retain the same format as Figure 7. Figure 9 illustrates the components of the computed damping in terms of basic damping types, i.e., skin friction viscous damping, eddymaking damping except for the bilge keel, bilge keel damping except for lift, and the wavemaking damping. Figure 10, on the other hand, presents the damping provided individually by the hull and skeg, the rudders, the propeller shaft brackets and bilge keels. The importance of the speed dependent and roll angle independent dynamic lift damping, B_L, as a portion of the total damping at even a relatively modest speed of 9 knots is quite well illustrated in Figure 9, as is the essentially insignificant contribution of the skin friction. The impact of the speed dependence on the eddymaking damping is also illustrated.

The relative importance of the hull and skeg as roll damping sources is illustrated in Figure 10 as is the insignificance, at least for the DE-1006, of the propeller shaft brackets.

CONCLUDING REMARKS

The components of roll damping computed in SMP and considered in this report are for "normal" ships. Certain components which are ignored as being insignificant for "normal" ships should be recognized when necessary; for example, wave damping due to very large bilge keels mounted near to the free surface.

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Figure 1 - Computer-Generated Body Lines

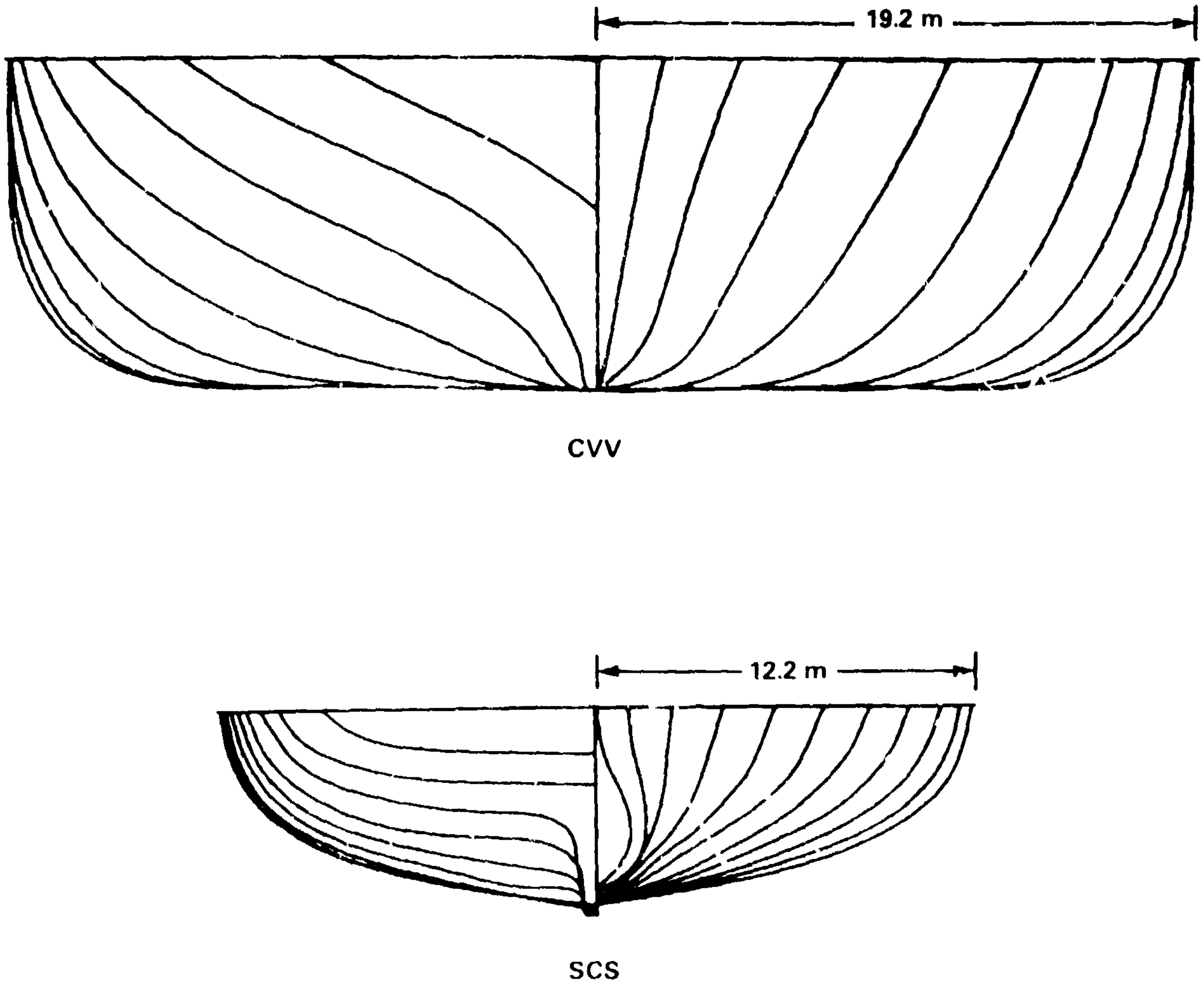
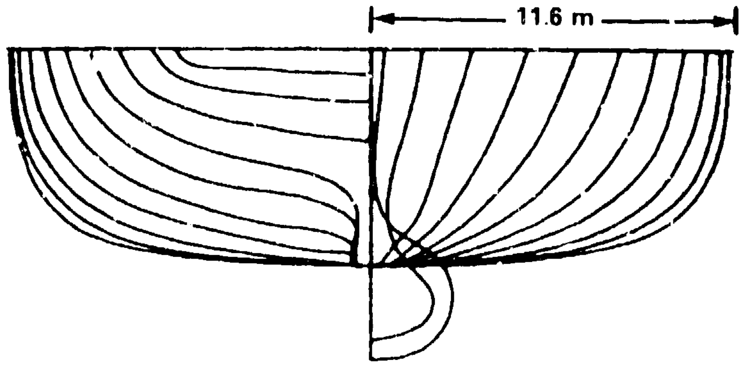
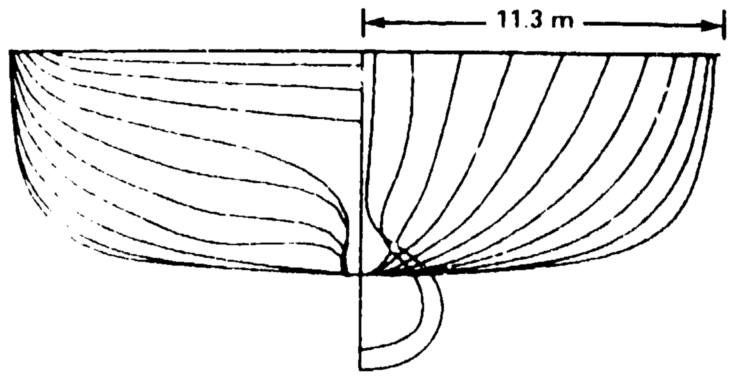


Figure 1a - Class 1 Underwater Hull Forms

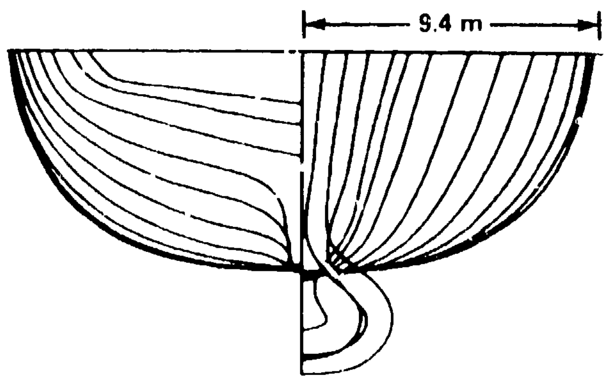
Figure 1 (Continued)



CSGN-CONVENTIONAL HULL



CSGN-LWP HULL



CGN-42

Figure 1b - Class 2 Underwater Hull Forms

Figure 1 (Continued)

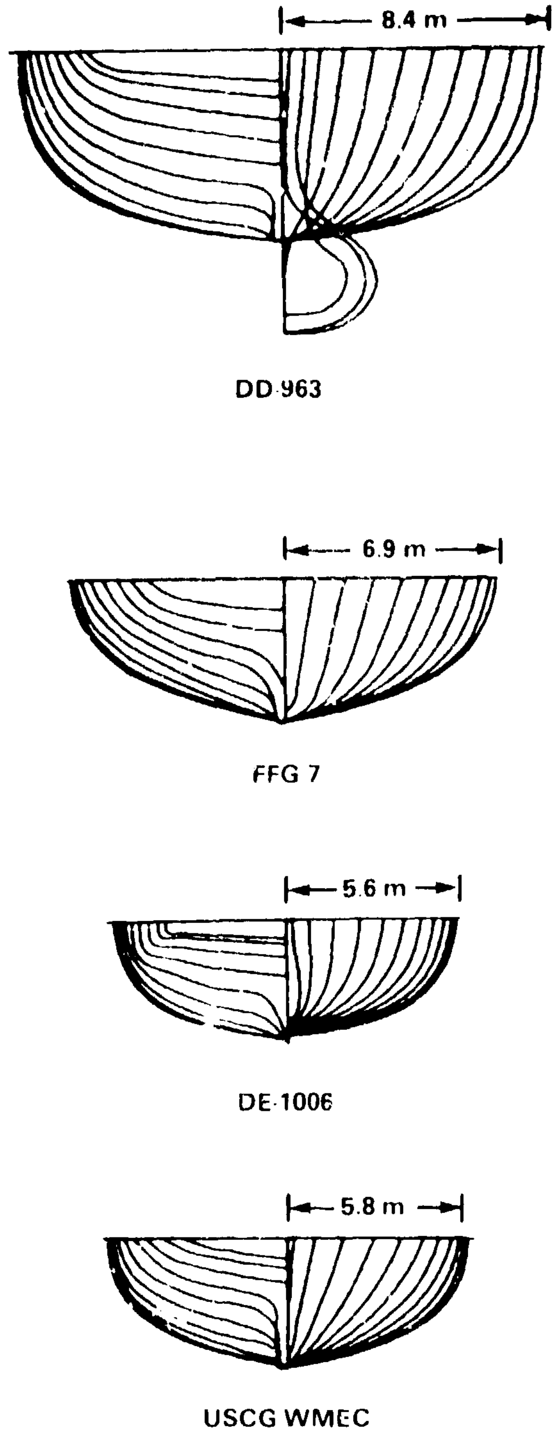


Figure 1c - Class 3 Underwater Hull Forms

Figure 1 (Continued)

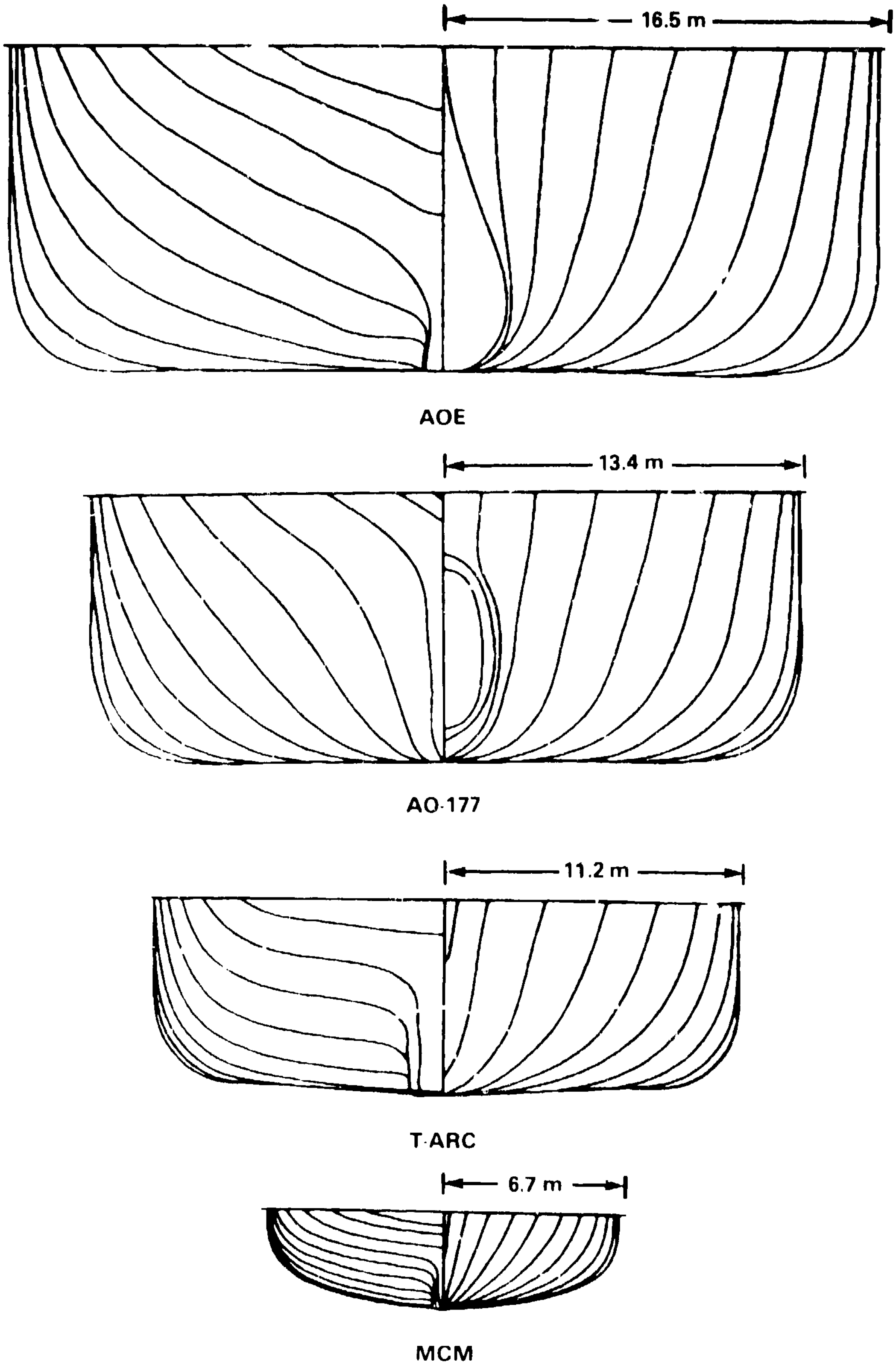


Figure 1d - Class 4 Underwater Hull Forms

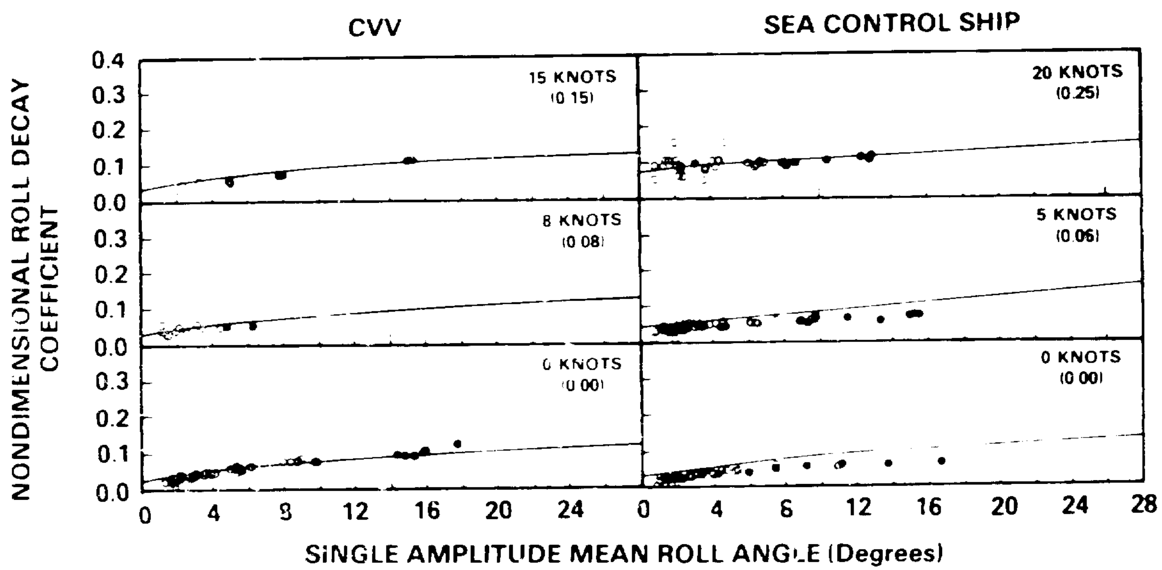


Figure 2 - Comparison of Experimental and Analytical Roll Decay Coefficients for Class 1 Ships

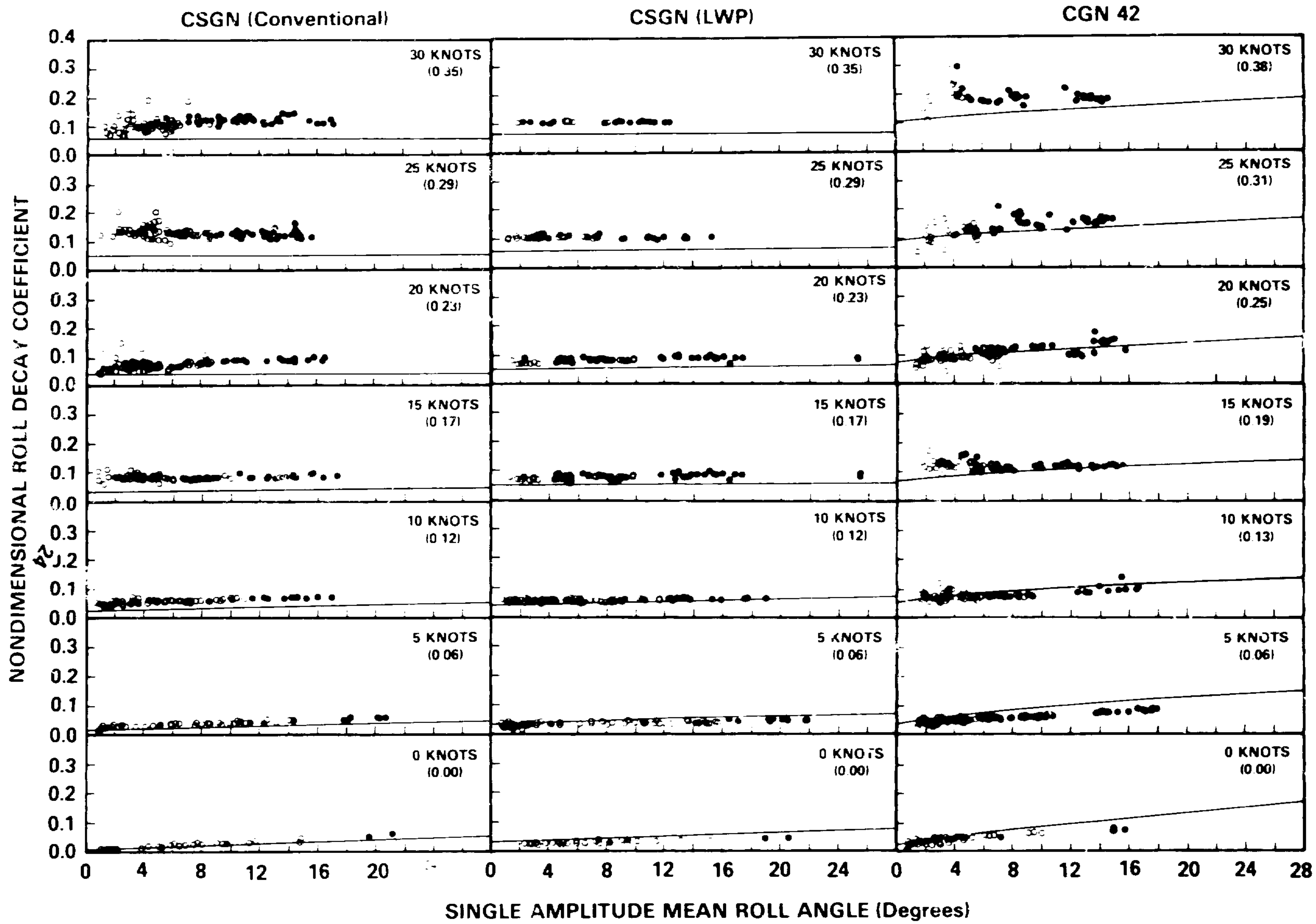


Figure 3 - Comparison of Experimental and Analytical Poll Decay Coefficients for Class 2 Ships

Figure 4 - Comparison of Experimental and Analytical Roll Decay Coefficients for Class 3 Ships

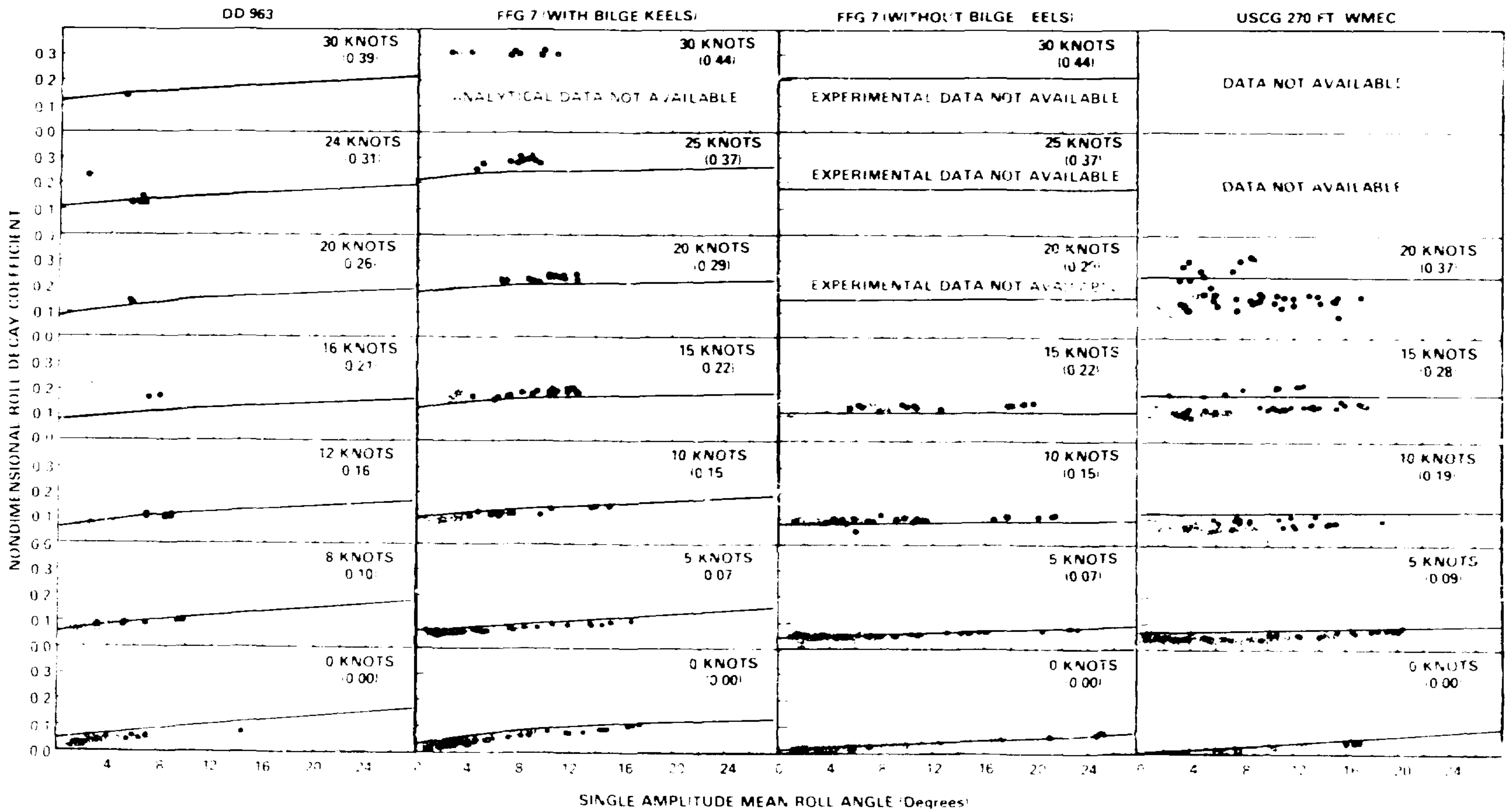


Figure 4a - Comparison of the DD-963, FFG-7 With and Without Bilge Keels, and the USCG WMEC

Figure 4 (Continued)

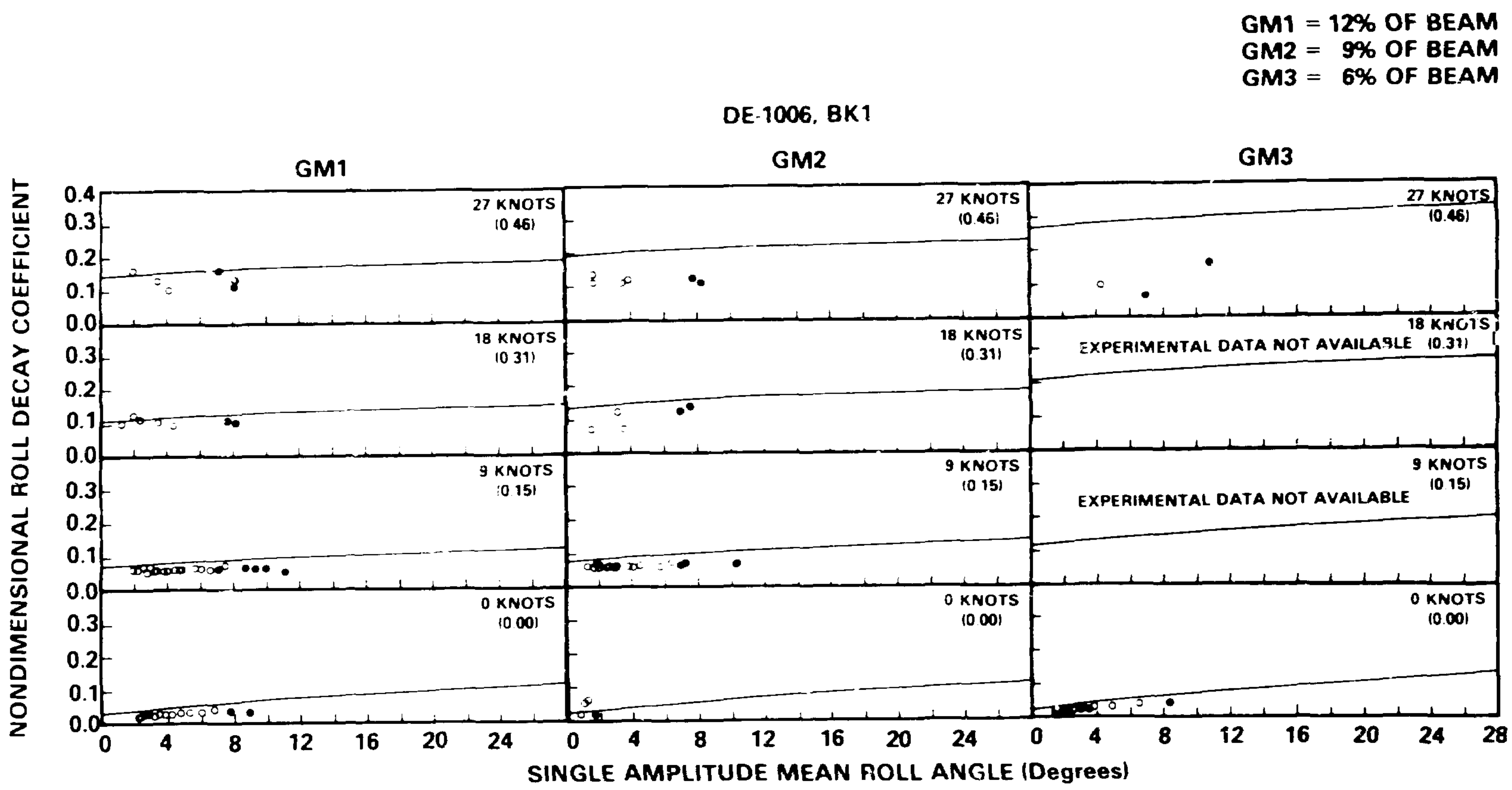


Figure 4b - Comparison of the DE-1006 for Three CM Values and a 91.2-Foot (27.8-Meter) Bilge Keel

Figure 4 (Continued)

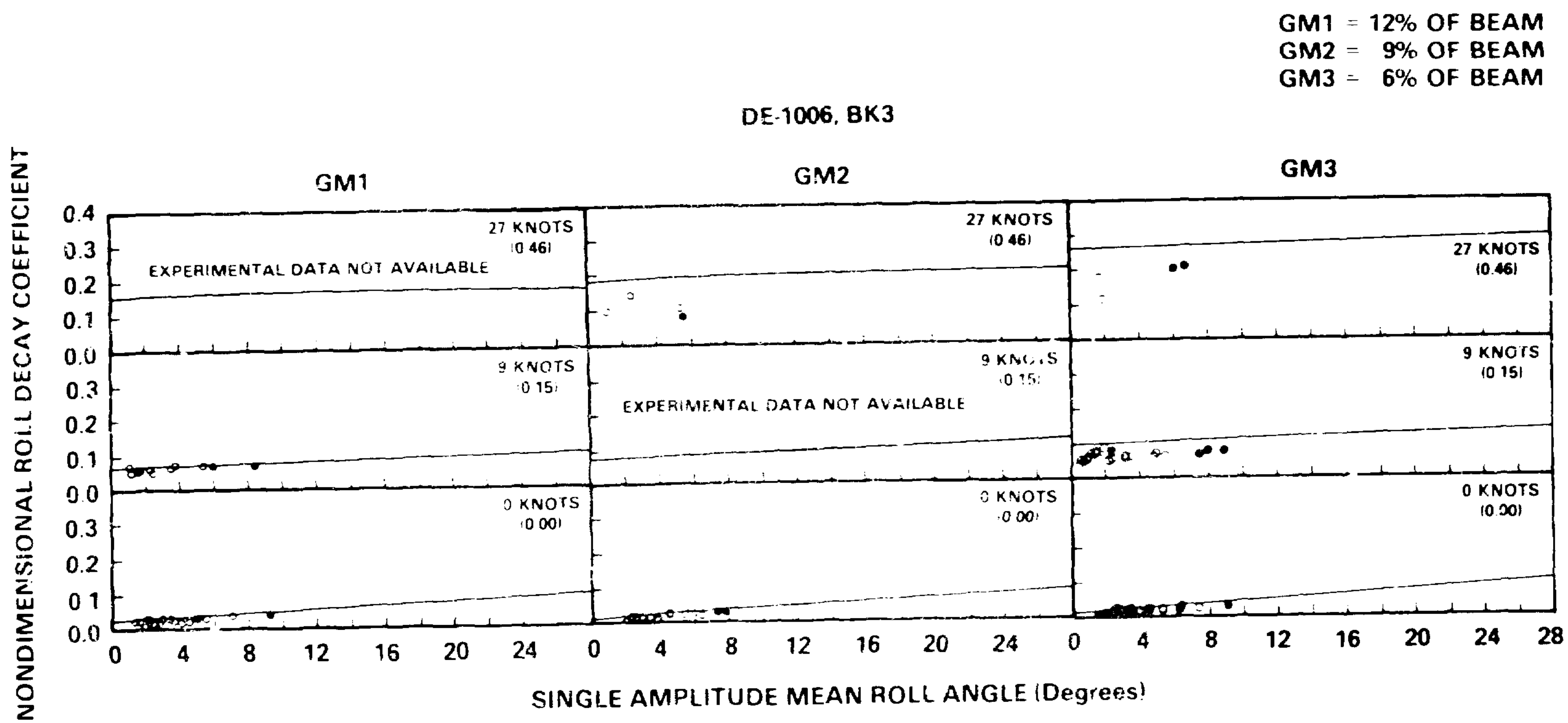


Figure 4c - Comparison of the DE-1006 for Three GM Values and a 32.4-Foot (16-Meter) Bilge Keel

Figure 4 (Continued)

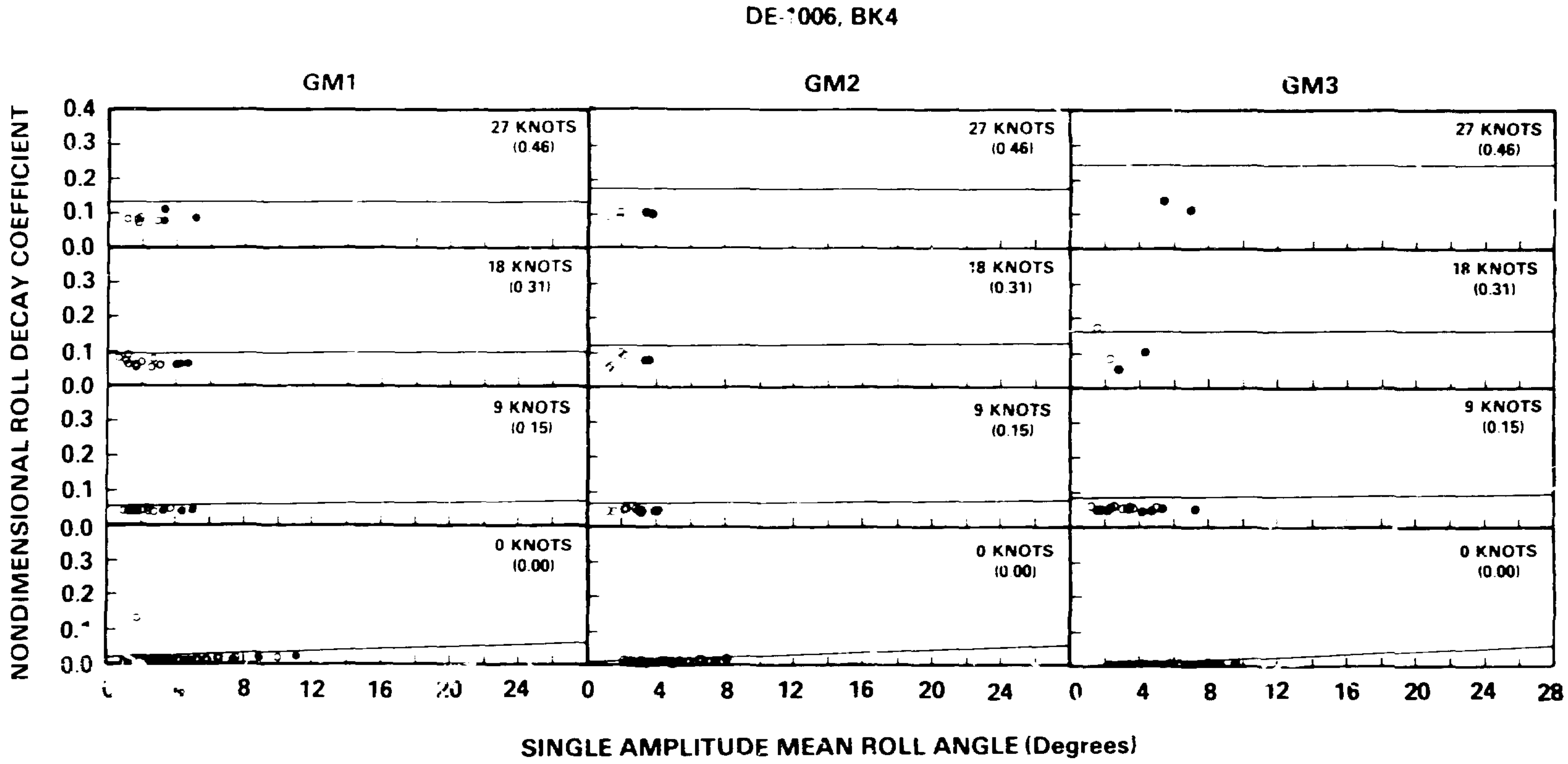


Figure 4d - Comparison of the DE-1006 for Three GM Values and No Bilge Keel

Figure 5 - Comparison of Experimental and Analytical Roll Decay Coefficients for Class 4 Ships

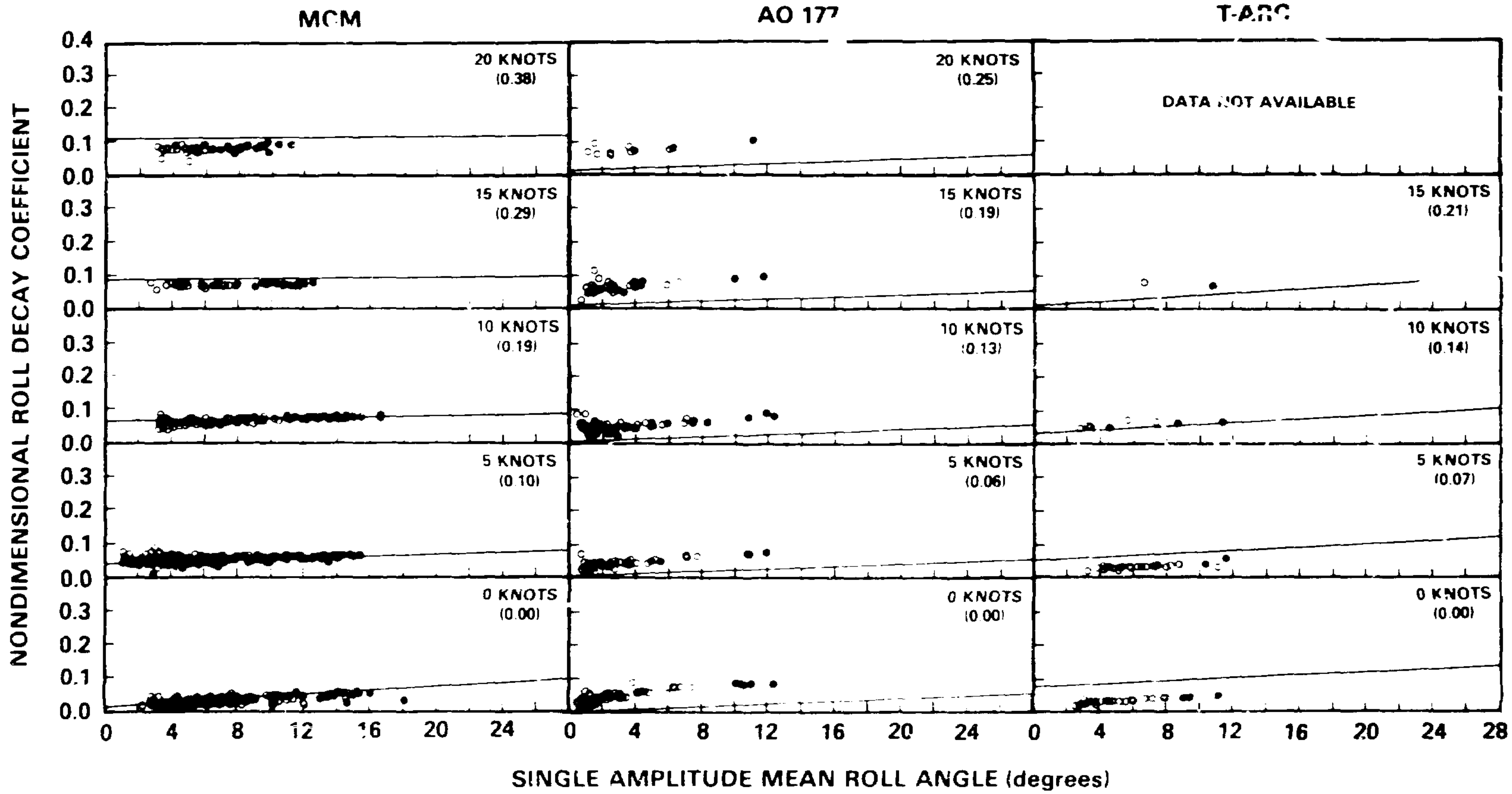


Figure 5a - Comparison of the MCM, AO-177, and T-ARC

Figure 5 (Continued)

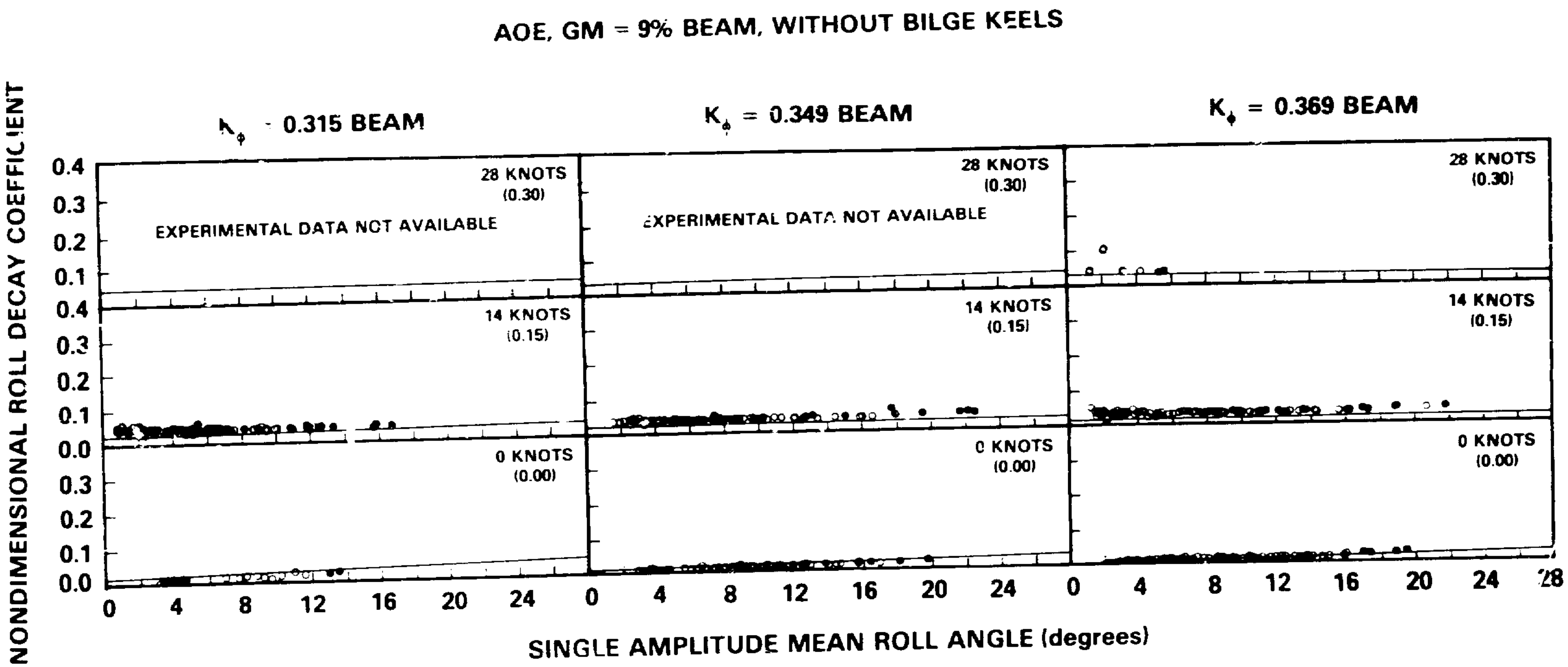


Figure 5b - Comparison of the AOE for Three Roll Gyradii (K_ϕ) Values and No Bilge Keel

Figure 5 (Continued)

AOE, GM = 6% BEAM, K_ϕ = 0.349 BEAM

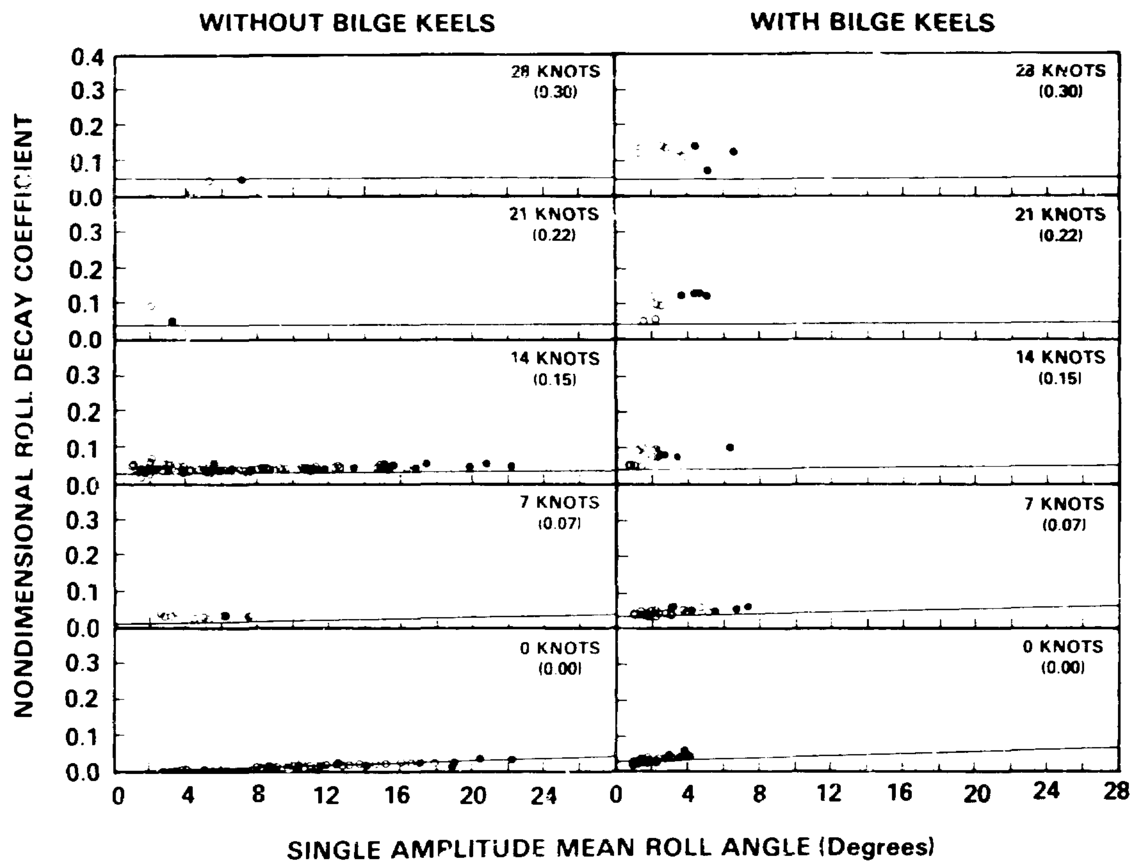


Figure 5c - Comparison of the AOE With and Without Bilge Keels

Figure 5 (Continued)

AOE WITHOUT BILGE KEELS, K_ϕ = 0.343 BEAM

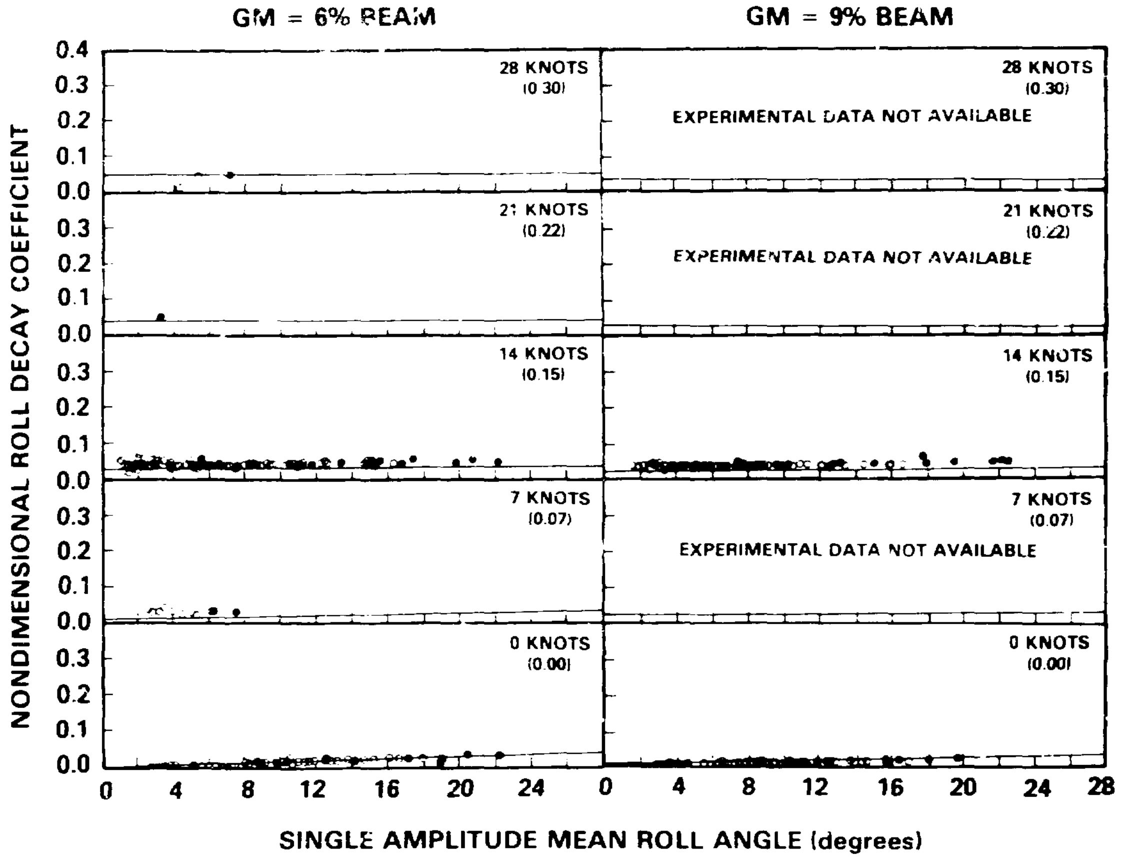


Figure 5d - Comparison of the AOE for Two GM Values Without Bilge Keels

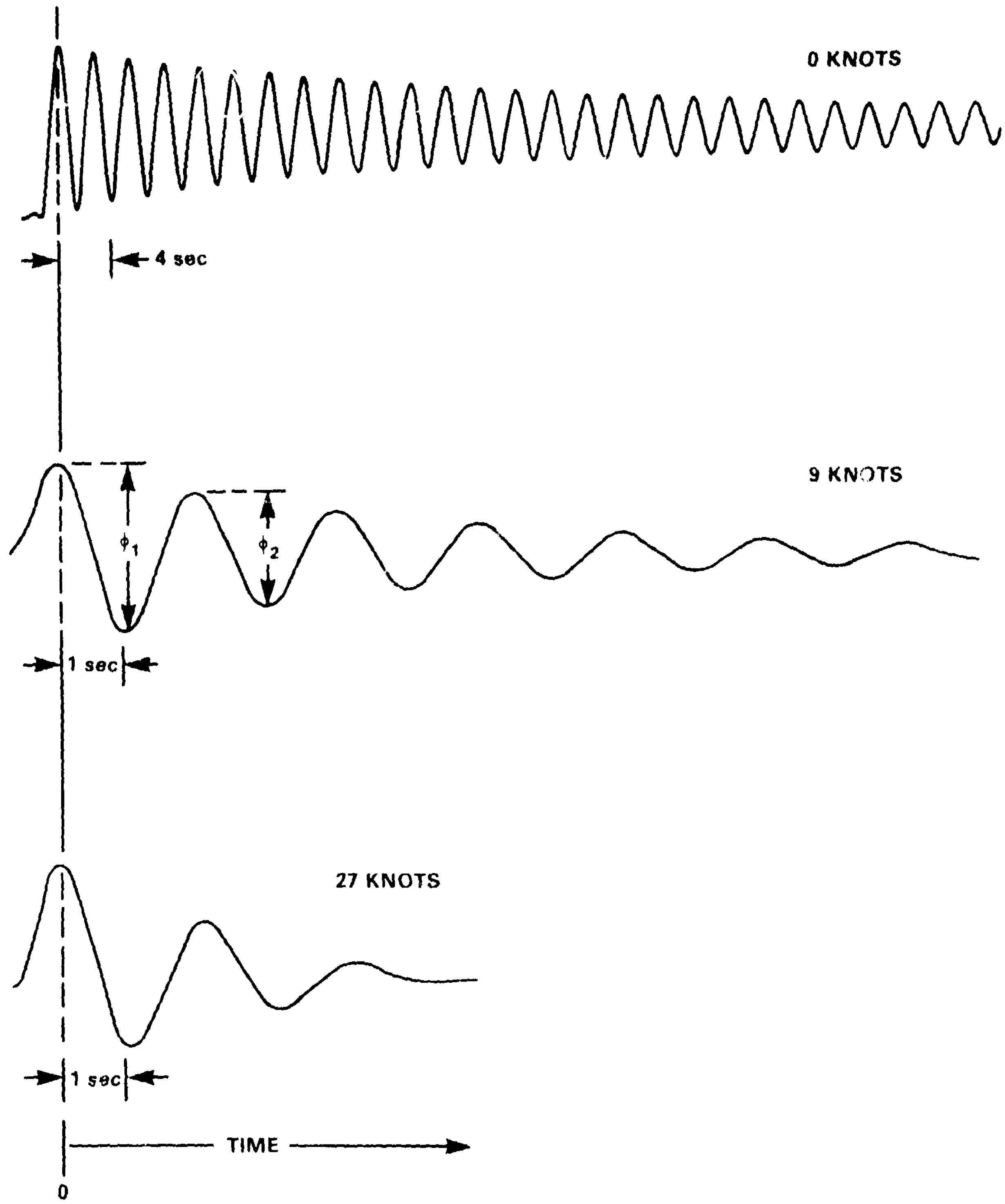


Figure 6 - Actual Roll Decay Records from Model Experiments With the DE-1006, GM3 Without Bilge Keels

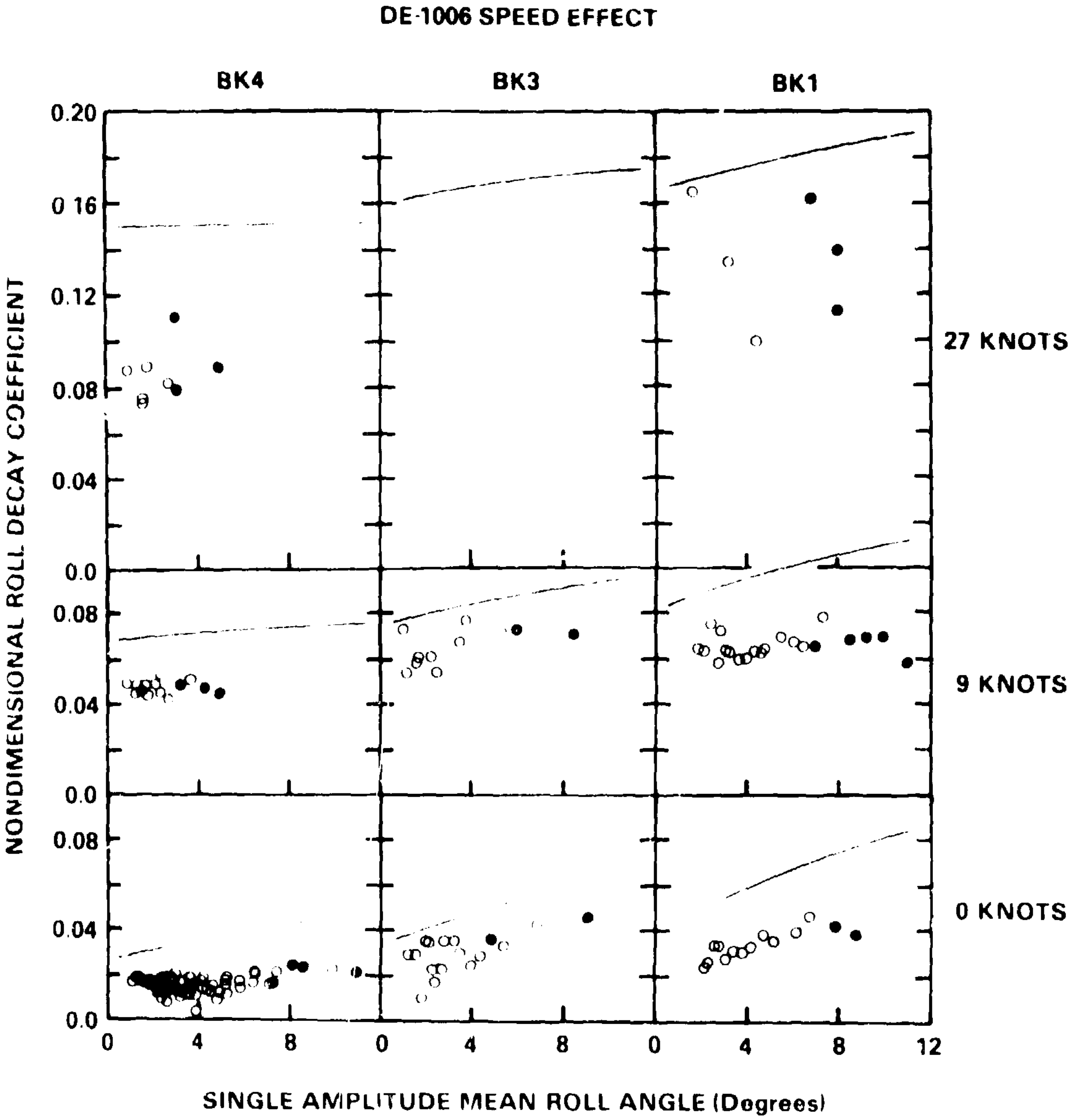


Figure 7 - Comparison Between Measured and Calculated (SMP) Roll Decay Coefficients: Speed Effect for Various Bilge Keel Sizes for the DE-1006, GM1

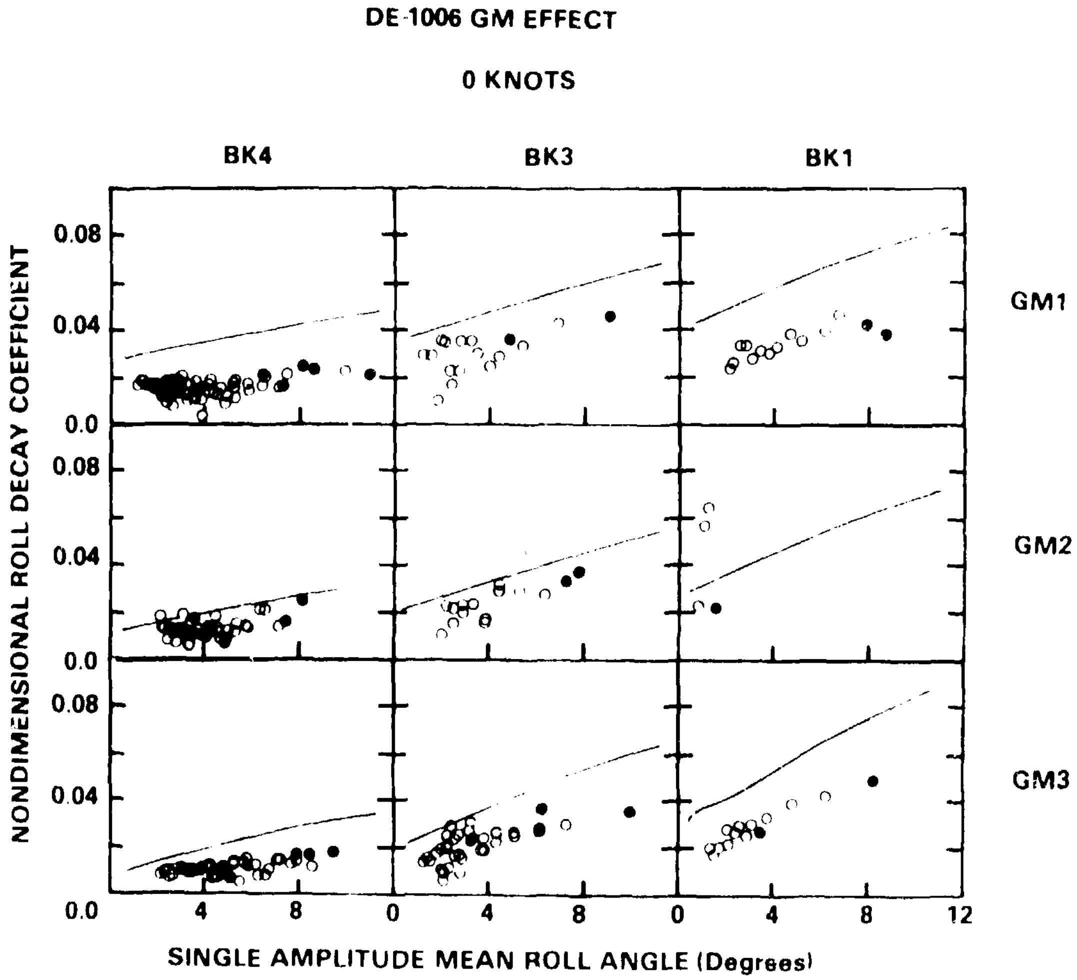


Figure 8 - Comparison Between Measured and Calculated (SMP) Roll Decay Coefficients: GM Effect for Various Bilge Keel Sizes for the DE-1006, 0 Knots

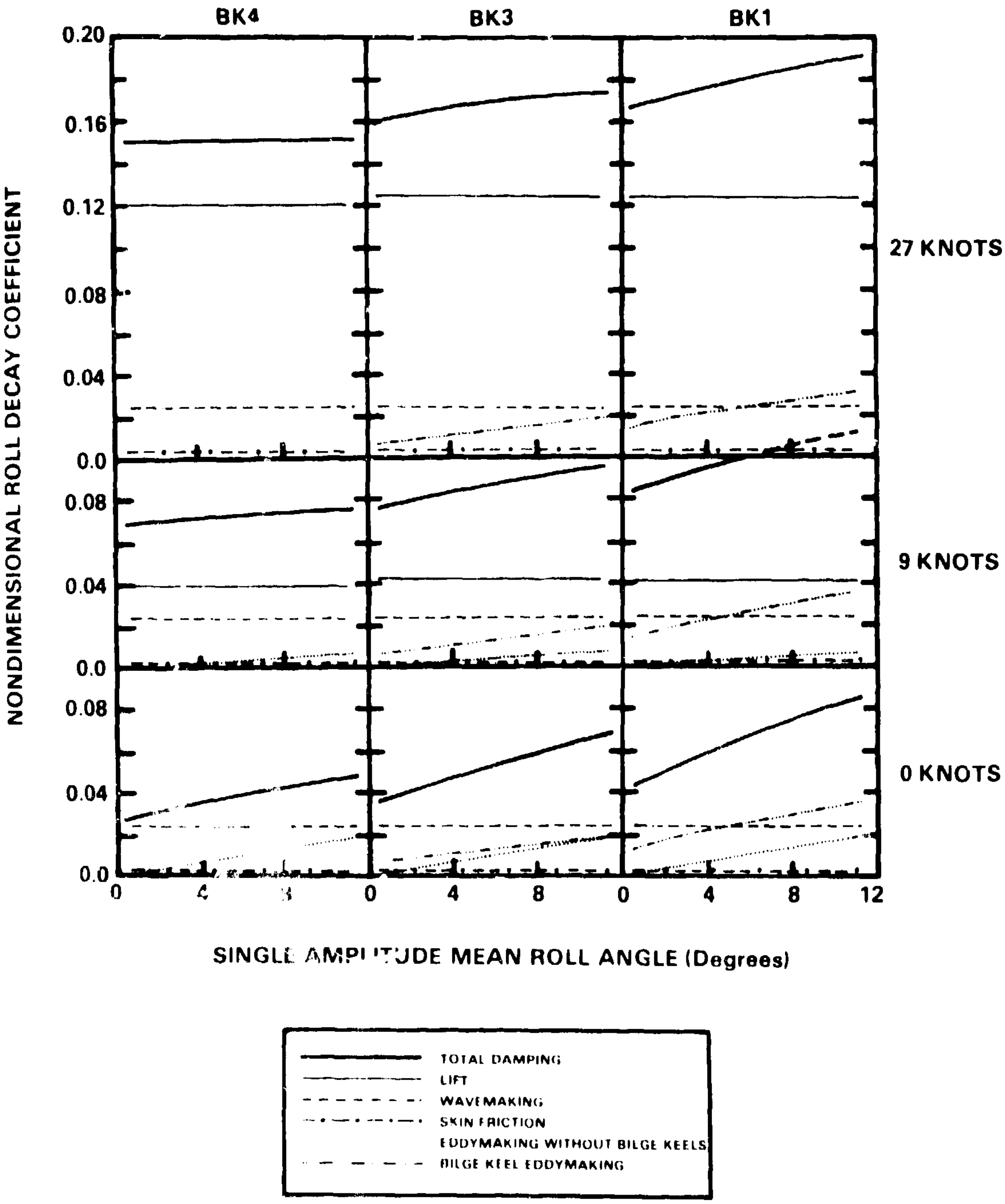


Figure 9 - Components (Lift, Wavemaking, Skin Friction, etc.) of the Calculated Roll Decay Coefficient for the DE-1006, GMJ

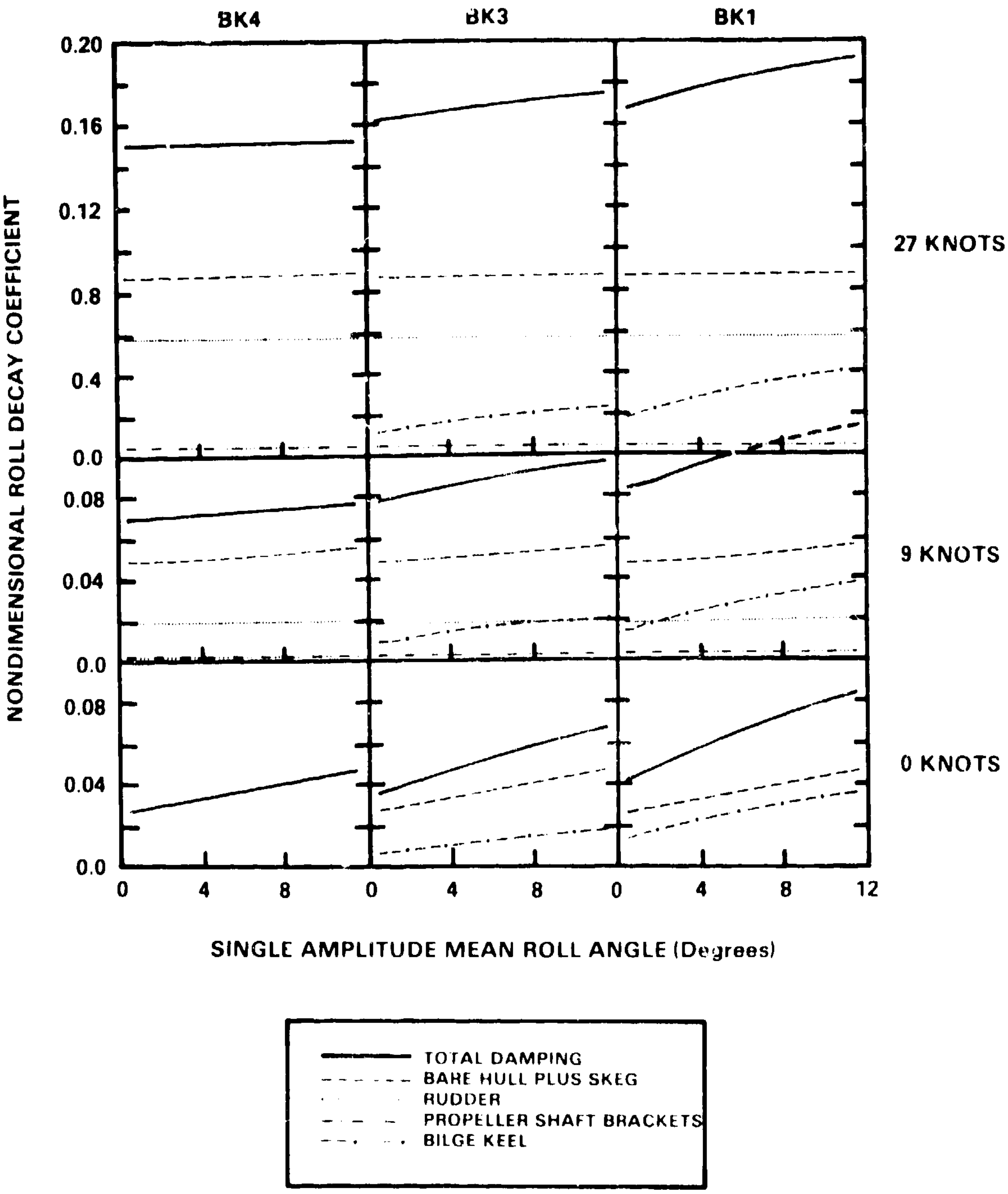


Figure 10 - Components (Bare Hull plus Skeg, Rudder, Bilge Keels, etc.) of the Calculated Roll Decay Coefficient for the DE-1006, GM1

TABLE 1 - COMPARISON OF SHIP PARTICULARS

Ship	Length Lpp (ft m)	Beam (ft m)	Draft (ft m)	Displacement Long Tons Metric Tons	GM % Beam	KG % Beam	LCG % Lpp	LCF % Lpp	Estimated Roll Period (seconds)	Roll Gyradius % Beam	Pitch Gyradius (% Lpp)	Yaw Gyradius (% Lpp)	Block Coefficient C_B
Class 1													
CVN	860.0 262.1	126.0 38.4	34.30 10.4	60,487 59,277	10.5	48.2	52.4	54.9	19.31	40.0	25.0	25.0	0.59
SCS	585.0 178.3	79.8 24.3	20.40 6.2	12,590 12,338	14.5	39.2	53.7	57.4	13.25	46.0	24.7	24.7	0.47
Class 2													
CSGN (VP)	666.0 203.0	74.1 22.6	22.50 6.9	16,551 16,220	15.3	39.1	51.3	58.0	9.54	35.0	25.0	25.0	0.54
CSGN (CONV)	666.0 203.0	75.8 23.1	22.15 6.8	16,594 16,262	9.7	36.3	51.2	55.5	12.10	35.0	25.0	25.0	0.53
CGN-42	560.0 170.7	61.9 18.9	22.70 6.9	11,715 11,481	6.9	40.4	51.5	56.9	12.99	35.0	25.0	25.0	0.53
Class 3													
DD-963	529.0 161.2	54.8 16.7	19.60 6.0	7,677 7,523	7.1	40.2	51.2	58.1	12.73	37.0	25.0	25.0	0.49
FFG-7	408.0 124.4	44.3 13.5	14.84 4.5	3,449 3,380	7.3	44.5	50.4	55.3	10.72	35.0	25.0	25.0	0.46
DE-1006*	308.0 93.9	36.5 11.1	12.13 3.7	1,872 1,835	12.3	36.9	51.7	56.7	7.19	35.0	25.0	25.0	0.51
USCG WMEC	255.0 77.7	38.0 11.6	13.50 4.1	1,625 1,651	5.7	47.3	50.9	55.6	11.17	35.0	25.0	25.0	0.46
Class 4													
AOE*	788.0 240.2	108.0 32.9	38.70 11.8	52,189 51,145	12.0	29.5	50.6	55.8	10.70	28.0	25.0	25.0	0.57
AO-177	550.0 167.6	88.0 26.8	32.20 9.8	26,278 25,752	8.3	32.5	50.7	53.6	14.13	35.0	25.0	25.0	0.61
T-ARC	464.0 141.4	73.0 22.3	23.70 7.2	13,816 13,540	4.2	42.1	50.9	54.5	23.27	45.0	25.0	25.0	0.60
MCM	240.0 73.2	44.0 13.4	11.87 3.6	1,681 1,647	14.3	40.3	51.9	56.6	7.61	35.0	25.0	25.0	0.48

*Base Load Condition

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